

DISCOVERY OF A ~ 1 Hz QUASI-PERIODIC OSCILLATION IN THE LOW-MASS X-RAY BINARY 4U 1746–37

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ABSTRACT

We have discovered a ~ 1 Hz quasi-periodic oscillation (QPO) present in the persistent X-ray emission of the globular cluster source, dipper, and low-mass X-ray binary (LMXB) 4U 1746–37. The QPO was also observed during type I X-ray bursts. The QPO properties resemble those of QPOs found recently in the LMXB dippers 4U 1323–62 and EXO 0748-676, which makes 4U 1746–37 the third source known to exhibit this type of QPO. We present evidence for X-ray spectral changes in this source similar to those observed in LMXBs referred to as atoll sources. We detect two states, a lower intensity and spectrally hard state and a higher intensity and spectrally soft state. This may explain the different spectral characteristics reported for 4U 1746–37 earlier. The high-intensity state resembles the banana branch state of atoll sources. The QPOs are seen only in the low-intensity state and are absent when the source is in the banana branch. This strongly suggests that either the accretion disk or an extended central source changes shape between the low-intensity state and the banana branch. Twelve bursts were detected, of which five took place while the source was on the banana branch and seven while the source was in the low-intensity state. The bursts occurring on the banana branch had an e -folding time ~ 3 times longer than those that occurred in the low-intensity state. Whereas previously detected dips showed a decrease in count rate of only $\sim 15\%$, we found a dip in one observation for which the count rate dropped from ~ 200 counts s^{-1} to ~ 20 counts s^{-1} . This dip lasted only ~ 250 s, during which clear spectral hardening occurred. This is the first time strong evidence for spectral changes during a dip have been reported for this source.

Subject headings: accretion, accretion disks — stars: individual (4U 1746–37) — stars: neutron — X-rays: stars

1. INTRODUCTION

The low-mass X-ray binary (LMXB) 4U 1746–37 shows type I X-ray bursts (Li & Clark 1977) and dips (Parmar et al. 1989), which recur on the 5.7 hr (Sansom et al. 1993) orbital period. The source is located in the globular cluster NGC 6441. Deutsch et al. (1998) reported the probable detection of the optical counterpart. The dips in dip sources such as 4U 1746–37 are thought to be caused by periodic obscuration of the central source by a structure formed in an interplay between the accretion stream from the companion toward the disk and the disk itself (White & Swank 1982; White, Nagase, & Parmar 1995; Frank, King, & Lasota 1987). This structure moves through the line of sight, fully or partially obscuring the central source once each binary cycle. Often, the X-ray spectral properties change during the dips. Spectral hardening occurs in 4U 1323–62 (Parmar et al. 1989), and spectral softening in deep dips is

seen in 4U 1624–49 (Church & Balucińska-Church 1995). In 4U 1746–37 no energy dependence has been found so far (Sansom et al. 1993). The type I X-ray bursts are observed to have peak luminosities around the Eddington luminosity for the estimated distance to the globular cluster (10.7 kpc; Djorgovski 1993). With the fact that the ratio of the X-ray to optical luminosities $L_X/L_{opt} \sim 10^3$, this makes it likely that outside the dips the central source is viewed directly (Parmar et al. 2000).

Recently, in two dipping LMXBs, 4U 1323–62 (Jonker, van der Klis, & Wijnands 1999) and EXO 0748-676 (Homan et al. 1999), quasi-periodic oscillations (QPOs) with a typical frequency of 1 Hz were discovered. In EXO 0748-676 these frequencies vary between 0.58 and 2.44 Hz on timescales ranging from several days to weeks (Homan et al. 1999). Observations with intervals of several days to weeks revealed similar frequency shifts in 4U 1323–62 (P. G. Jonker et al. 2000, in preparation). These QPOs are strong, with fractional rms amplitudes of $\sim 10\%$, which are the same in the persistent emission, during dips, and during type I X-ray bursts. The rms amplitude of the QPOs does not depend (or only weakly depends) on the photon energy, unlike that of other types of QPOs observed from LMXBs (van der Klis 1995, 1998). From these properties and the fact that the ~ 1 Hz QPOs are observed in high-inclination systems, Jonker et al. (1999) suggested that partial obscuration of the central source by a nearly opaque or gray medium in or on the disk covering and uncovering the source quasi-periodically at the observed QPO frequency could explain the QPO properties. The most natural location for such a medium would be at the radius for which the orbital frequency in the disk is equal to the QPO frequency,

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which corresponds to a radius of $\sim 2 \times 10^8$ cm for a $1.4 M_{\odot}$ neutron star (Jonker et al. 1999).

On the basis of the timing and spectral properties of LMXBs, Hasinger & van der Klis (1989) defined the atoll and the Z sources. The atoll sources show at least two states, named after the associated structures in the X-ray color-color diagram (CD): the island and the banana branch. The timing and spectral properties of the sources in these states are different. In the island state strong band-limited noise is present in the power spectra. When the source moves up the banana branch, the fractional rms amplitude of this noise component decreases and simultaneously the rms amplitude of a very low-frequency power-law noise (VLFN) component increases. The Z sources have higher luminosities and trace out a Z track in the CD. The timing properties are correlated with the position along this track (for a complete overview of the timing and spectral properties of the atoll and Z sources, see van der Klis 1995).

In this paper, we report the discovery of a ~ 1 Hz QPO in the source 4U 1746–37. We also show that the spectral characteristics and some of the timing properties of this source are reminiscent of those of an atoll source.

2. OBSERVATIONS AND ANALYSIS

We analyzed nine observations of 4U 1746–37 obtained with the Proportional Counter Array (PCA) on board the *RXTE* satellite (Bradt, Rothschild, & Swank 1993) in 1996 on October 25, 27, 31, and in 1998 on June 5, June 6, August 3, November 7, and November 22. The total amount of good data analyzed was ~ 129 ks. A log of the observations can be found in Table 1. Data were obtained over the energy range 2–60 keV simultaneously with time resolutions of 0.125 s, 16 s, and 1 μ s in 1, 129, and 255 energy bins, the Standard 1, Standard 2, and GoodXenon data modes, respectively.

The average persistent emission count rates varied from 66 counts s^{-1} (observation 3) to nearly 800 counts s^{-1} (observation 9; see Table 1). Unless otherwise stated, all count rates reported are for five PCA detectors and are background subtracted. We observed shallow dips in the light curve showing a decrease in count rate of only $\sim 15\%$ and one deep dip with evidence for spectral hardening (see Fig. 1 and § 3). During the last part of observation 9 a solar flare occurred; we excluded these data from our analysis.

Since the dips were often difficult to distinguish from the persistent emission (Sansom et al. 1993; Parmar et al. 2000), we divided the data into just two categories; nonburst

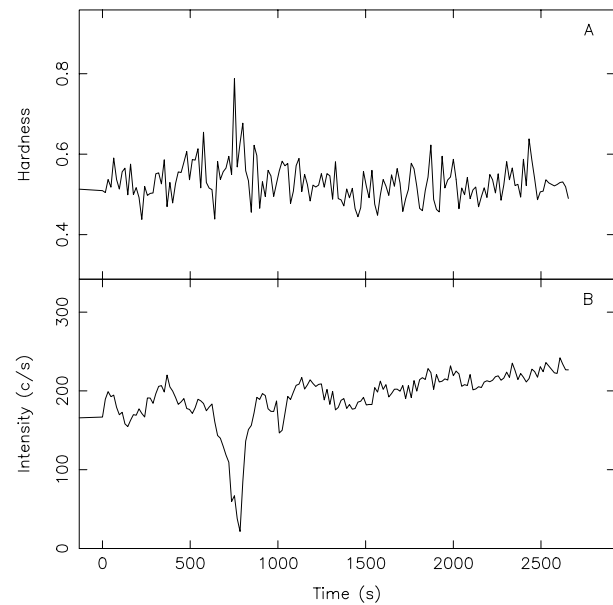


FIG. 1.—(a): Hardness curve (ratio between the count rates in the 9.7–16 and in the 2–9.7 keV bands) of the last part of observation 7 (time zero corresponds to August 3, 14:15:03 UTC). (b): Simultaneous 2–60 keV, background-subtracted light curve, clearly showing spectral hardening during the dip. No dead-time corrections were applied (the dead-time fraction was less than 1.5%). Since the photon-photon dead time is completely negligible both in and outside the dip, the dead time does not affect the hardening during the dip.

(which combines persistent emission and dip data) and burst data.

For the selection of the burst data, the start of a burst was characterized by the sharp increase in flux and simultaneous decrease in hardness. The burst e -folding time was determined by fitting an exponential function to the burst decay in the 2–60 keV light curve of the Standard 1 data. The end of the burst was chosen to be three times the e -folding time after the onset (see also Jonker et al. 1999).

Using the GoodXenon data, we calculated power spectra of nonburst data segments 64 s long and of burst data segments 16 s long in the energy bands 2–60, 2–6.4, and 6.4–60 keV, with a Nyquist frequency of 512 Hz. We also calculated power spectra of segments 16 s long with a Nyquist frequency of 2048 Hz in the 2–60 keV band. The power spectra within each energy band were added and averaged for each observation, separately for burst and nonburst data. To search for burst oscillations, we also cal-

TABLE 1
LOG OF OBSERVATIONS

Observation	ID	Date	Start Time (UTC)	Amount of Good Data (ks)	Persistent Emission (counts s^{-1}) ^a
1	10112-01-01-00	1996 Oct 25	00:10:55	~ 22	73
2	10112-01-01-01	1996 Oct 27	03:25:07	~ 17	73
3	10112-01-01-02	1996 Oct 31	08:26:19	~ 21	66
4	30701-11-01-00	1998 Jun 5	00:09:55	~ 6	365
5	30701-11-01-01	1998 Jun 5	14:09:03	~ 15	415
6	30701-11-01-02	1998 Jun 6	07:45:43	~ 3	414
7	30701-11-02-00	1998 Aug 3	03:15:03	~ 25	296
8	30701-11-03-01	1998 Nov 7	08:19:37	~ 7	728
9	30701-11-04-00	1998 Nov 22	11:18:33	~ 13	785

^a Five-detector average 2–60 keV persistent emission count rate for each observation.

culated power spectra of length 1 s with a Nyquist frequency of 2048 Hz.

We constructed a CD from all nonburst Standard 2 data, using four detectors (0, 1, 2, and 3). The hard color in this diagram is defined as the logarithm of the ratio of the count rates in the 9.7–16.0 keV band to the count rates in the 6.0–9.7 keV band, and the soft color is defined as the logarithm of the ratio of the count rates in the 3.5–6.0 keV band to the count rates in the 2–3.5 keV band.

3. RESULTS

In the nonburst data of 1996 October 25 (observation 1), we discovered a QPO in the 2–60 keV band with frequency, FWHM, and rms amplitude 1.04 ± 0.03 Hz, 0.36 ± 0.09 Hz, and $7.7\% \pm 0.7\%$ (6σ), respectively (see Fig. 2). In the observations of October 27 (observation 2) and October 31 (observation 3) 1996, we observed QPOs with similar frequencies, FWHMs and rms amplitudes, albeit at a lower significance level (see Table 2).

We measured the QPO properties in the 2–6.4 and 6.4–60 keV bands. Upper limits on the presence of the QPO were derived by fixing the values of the FWHM and fre-

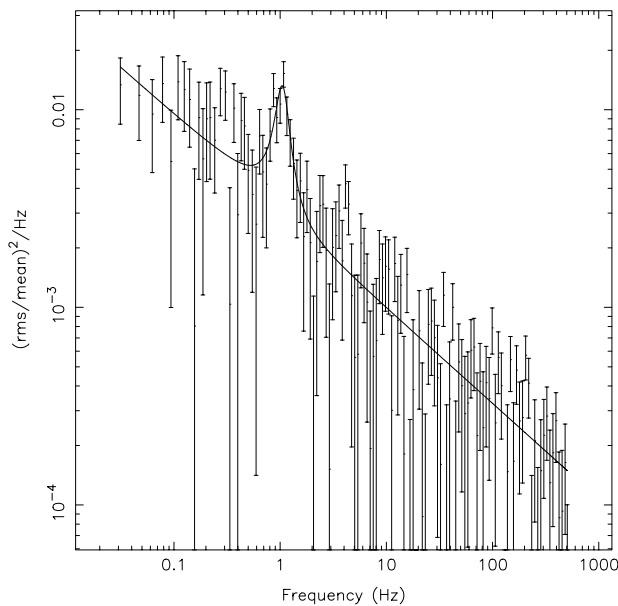


FIG. 2.—Normalized (van der Klis 1988) power spectrum of observation 1. The Poisson noise has been subtracted. The solid line represents the best fit to the data using two components in the fit: a Lorentzian at ~ 1 Hz (the QPO) and a power law.

quency obtained in the 2–60 keV energy band, except for observation 2. For this observation we used the values obtained in the 2–6.4 keV band, since the QPO was not detected at a significance level higher than 3σ in the 2–60 keV band (see Table 2). Only for observation 1 was the QPO detected at a significance higher than 3σ in both the 2–6.4 and the 6.4–20 keV energy bands. Within the errors, the rms amplitude of the QPO in the two energy bands was the same (see Table 2).

The QPO was also detected when all 16 s segment power spectra (nine in total) of the decay of the three bursts of observation 1 were combined at a similar fractional rms amplitude ($7.2\% \pm 0.8\%$). The average count rate was ~ 720 counts s^{-1} , i.e., about 10 times that in the persistent emission. The frequency increased significantly with respect to the frequency of the QPO in the persistent emission to $1.39^{+0.05}_{-0.10}$ Hz. The FWHM of the QPO was consistent with that in the persistent emission. In the bursts of observations 2 and 3, no significant QPO was detected; upper limits on the rms amplitude were 7% to 8%.

We fitted a power law to the noise component evident in Figure 2. Its rms amplitude integrated over 0.0156–1 Hz varied from $7.1\% \pm 0.3\%$ to $5.9\% \pm 0.4\%$ and to $9.3\% \pm 0.4\%$ from observation 1–3, while the power-law index was consistent at 0.5 ± 0.3 . In observations 4–9, the noise amplitude was in the range 1.6%–5.7%. Here, the fractional rms amplitude increased with increasing intensities (see Table 1), except for observation 8, for which it was only 1.6%. The power-law indices ranged from 1.7 ± 0.4 to 2.1 ± 0.4 . The rms amplitude of this power-law component is slightly higher in the 6.4–20 than in the 2–6.4 keV band. The 6.4–20/2–6.4 keV spectral hardness did not significantly depend on the presence or absence of the QPO.

Combining all nonburst data into a CD, we observed a pattern that resembles the atoll shape (Hasinger & van der Klis 1989; Fig. 3). Two distinct parts can be distinguished in the CD, a hard (lower intensity, *upper part*), island-like state, and a softer (higher intensity, *lower part*) banana branch. The ~ 1 Hz oscillations were found only when the source was in the upper (hard) part of the diagram (composed of observations 1–3). Upper limits of 1%–2% on the presence of a QPO in the range 0.5–2.5 Hz were derived for the banana part of the diagram (composed of observations 4–9).

We observed a total of 12 type I bursts. One burst in the second observation and two bursts in the third observation showed secondary bursts, occurring several hundred seconds after the first burst and with a peak flux 3–4 times lower (see Lewin, van Paradijs, & Taam 1995). The burst *e*-folding times ranged from 7.5 to 11.3 s for bursts observed

TABLE 2

FRACTIONAL rms AMPLITUDES, FREQUENCIES, AND FWHMS FOR THE QPO 4U 1746–37 IN THE LOW-INTENSITY STATE

OBSERVATION	rms AMPLITUDE			ν_{QPO} (Hz)	FWHM (Hz)
	2–60 keV (%)	2–6.4 keV (%)	6.4–20 keV (%)		
1.....	7.7 ± 0.7	7.8 ± 0.9	$6.7^{+2.0}_{-1.1}$	1.04 ± 0.03	0.36 ± 0.09
2.....	<7	$6.9^{+1.2}_{-0.9}$	<6.8	1.59 ± 0.05	0.4 ± 0.2
3.....	$7.5^{+1.4}_{-1.1}$	<7.4	<8.7	1.01 ± 0.06	0.25 ± 0.13

NOTE.—If no QPO at a significance level higher than 3σ was detected, the 95% confidence upper limit is listed. The FWHM and the frequency were measured in the 2–60 keV band, except for observation 2, for which they were measured in the 2–6.4 keV band.

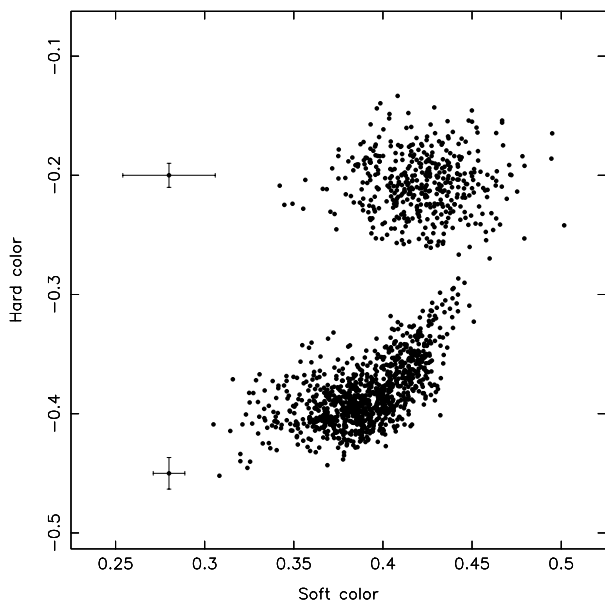


FIG. 3.—Color-color diagram of 4U 1746–37. The hard color is defined as the log of the 9.7–16.0 to 6.0–9.7 keV count rate ratio, the soft color as the log of the 3.5–6.0 to 2–3.5 keV ratio. No dead-time corrections have been applied (the dead time fraction was less than 2%). The data were background subtracted, and bursts were removed. Data points are 64 and 128 s averages for the banana branch (*lower part*) and for the presumed (see text) island state (*upper part*), respectively. Typical error bars are shown for data in the hard (island) state and for data on the banana branch.

in observations 1–3 and from 7.5 to 14.5 s for the secondary bursts. The burst e -folding time for four of the five bursts observed in observation 8 and 9 ranged from 27.7–30.1 s, while one burst in observation 9, which occurred ~ 600 s after a burst with a 2.3 higher peak flux, had an e -folding time of only 3.0 s (the peak flux of this very short burst was similar to that of the bursts in the low-intensity state). Upper limits on burst oscillations in the 100–1000 Hz frequency range during the peak and decay of the bursts of typically $\sim 15\%$ were derived, adding the different bursts.

One of the dips observed in observation 7 was different from the others; it showed a simultaneous sharp increase in hard color of $\sim 28\%$ and a drop in count rate from ~ 200 counts s^{-1} to ~ 21 counts s^{-1} . The dip was quite short (~ 250 s), whereas previous dips were shallow ($\sim 15\%$) and exhibited no clear spectral hardening (see Fig. 1). Because of the uncertainties in the orbital ephemeris, we could not relate the exact time of this deep dip to the dips in the other observations.

Upper limits on the presence of kHz QPOs in the frequency range 100–1000 Hz were derived using a fixed FWHM of 50 Hz. The upper limits were in the range 3.4%–6.5%.

4. DISCUSSION

We discovered a QPO in 4U 1746–37 with frequency ~ 1 Hz and rms amplitude $\sim 7.5\%$. The QPO was also observed during type I X-ray bursts for which the count rate was a factor of 10 higher, with similar fractional rms amplitudes. The QPO in 4U 1746–37 was observed only when the source intensity was low. The frequency of the QPO, the weak energy dependence of its rms amplitude, and the ratio Q of the QPO frequency to its FWHM are similar to the frequencies, rms amplitude energy depen-

dence, and Q -values (3–4) of the QPOs discovered recently in the persistent emission and dips, during the type I X-ray bursts in the dippers and LMXBs 4U 1323–62 (Jonker et al. 1999), and in EXO 0748–676 at low intensity (Homan et al. 1999). The similarities in QPO properties and the fact that 4U 1746–37 is a dipper suggest that a ~ 1 Hz QPO is a general property of high-inclination LMXBs at low intensities and that it has a common origin in these systems.

We found for the first time that 4U 1746–37 showed spectral characteristics of an atoll source; the timing properties of observations 4–9 were consistent with banana branch behavior reported for atoll sources (van der Klis 1995). Although no band-limited noise was detected, upper limits (1–512 Hz) in the low-intensity (hard) state were 20%–28%, whereas they were 2.5%–5.5% when the source was on the apparent banana branch. So, with respect to the band-limited noise, the timing behavior of the source is consistent with that of an atoll source. The fact that on the banana branch the rms amplitude of the power-law noise component increased as the source moved up in count rate is also consistent with the behavior of the VLFN on the banana branch of an atoll source. However, the high (5.9%–7.1%) rms amplitude and low power-law index (0.5) of the power-law noise component when the source is at low intensities is not consistent with island-state VLFN. We note that this could be due to effects observable only at high inclinations, similar to those that cause the dips and the ~ 1 Hz QPO. In EXO 0748–676 strong power-law noise (6%–11%) with indexes 0.5–0.8 was also present. This noise had no dependence or weak dependence on photon energy, just as the ~ 1 Hz QPOs (Homan et al. 1999) have, suggesting a similar origin for both phenomena. In the one observation of EXO 0748–676 for which no QPO was found, the rms amplitude of the VLFN was lower ($\sim 4\%$) and the power-law index was ~ 1 . The spectral changes we report in 4U 1746–37 related to changes in the position along the atoll probably reflect the changing spectral characteristics reported before for this source (eg. see Parmar et al. 2000).

Homan et al. (1999) found that the QPO in EXO 0748–676 was present in all observations except one, for which the persistent emission count rate was ~ 2.5 times higher than in the other observations. The fact that the QPO is not detected at higher source count rates (and inferred mass accretion rates) may be due to changes in the accretion geometry with \dot{M} . We expect that if we observe 4U 1323–62 at higher \dot{M} , the QPO may disappear as well. In 4U 1746–37 the QPO also disappeared when the count rate increased. The rms amplitude dropped by at least a factor of 5 when the source moved from the low-intensity state to the banana branch. This can be accounted for if the size of the central source increased by a factor of 2–3 in radius, decreasing the modulated fraction of the X-rays below our threshold of 1%–2%. If this is the explanation, the dip fraction should decrease, making the dips more shallow. Since in 4U 1746–37 the dips were shallow and the source count rates were low, we were not able to check this prediction for this source. Other possibilities are that the structure in or on the disk responsible for the ~ 1 Hz QPO disappeared or decreased in size or the optical depth of the gray medium changed.

We found that the burst e -folding time is shorter (~ 10 s) when the source is in the low-intensity state than when the source is on the higher intensity banana branch (~ 30 s). This is opposite to what was found by van Paradijs,

Penninx, & Lewin (1988) for several sources. Van der Klis et al. (1990) found that the burst duration for 4U 1636–53 was longer (> 20 s) when the source was in the island part of the CD than when the source was in the banana branch (< 10 s). Either the state where we observed the short burst e -folding times is not the product of an island state and high-inclination effects as we propose but a state at a higher mass accretion rate than the banana branch mass accretion rate or another parameter besides \dot{M} is also affecting the burst duration.

The frequency of the QPO was 0.35 Hz higher during the type I X-ray bursts than during the persistent emission of observation 1. Similar increases in the QPO frequency

during bursts were also observed in EXO 0748-676 by Homan et al. (1999).

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